

3rd Generation SUSY, Naturalness, and the Higgs

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Physics 290E

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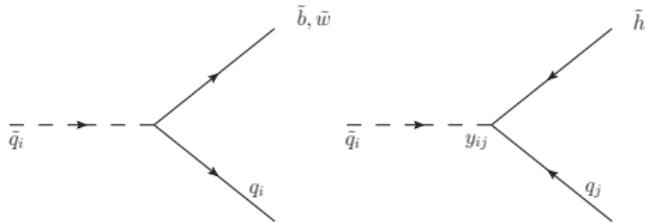
Outline

- ▶ Flavor physics
- ▶ Large yukawa couplings
 - ▶ Radiative EWSB
 - ▶ Fine tuning
 - ▶ Higgs mass and couplings
- ▶ Current experimental bounds

Flavor

- ▶ MSSM flavor, CP problems
- ▶ Minimal Flavor Violation: $U(3)^5$ broken only by yukawas
- ▶ e.g. $(m_Q^2)_{ij} = m_Q^2 \left(\delta_{ij} + (y_u y_u^\dagger)_{ij} + (y_d y_d^\dagger)_{ij} + \dots \right)$
- ▶ $y_d \approx 0 + \mathcal{O}\left(\frac{m_b \tan \beta}{m_t}\right)$, $y_u \approx \frac{1}{\sin \beta} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}\left(\frac{m_c}{m_t}\right)$

Flavor



- ▶ Loosely speaking, 3rd generation squarks tend to couple to 3rd generation quarks
- ▶ Flavor constraints are stronger for 1st and 2nd generation stuff
- ▶ Thus, new flavor violation can be largest when it involves 3rd generation stuff
- ▶ $b \rightarrow s\gamma$, baryonic RPV, ...

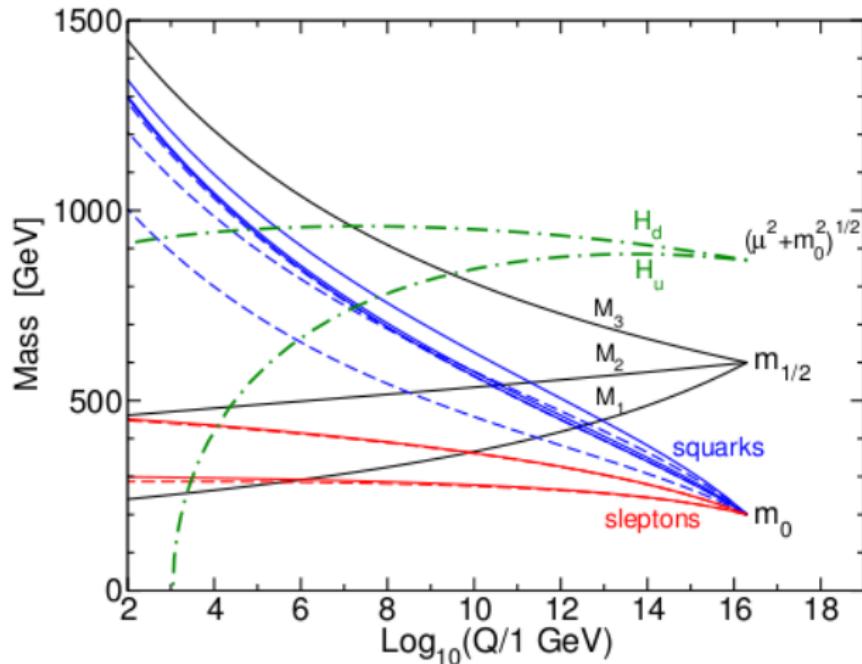
Radiative EWSB

- ▶ the MSSM is a 2HDM

$$\begin{aligned} V = & (|\mu|^2 + m_{H_u}^2) |H_u^0|^2 + (|\mu|^2 + m_{H_d}^2) |H_d^0|^2 + \\ & (B\mu H_u^0 H_d^0 + h.c.) + \frac{g^2 + g'^2}{8} (|H_u^0|^2 - |H_d^0|^2)^2 \end{aligned}$$

- ▶ usual story: running drives $m_{H_u}^2$ negative
- ▶ large top yukawa generates dominant contribution
- ▶ $B\mu$ term induces tadpole diagram for H_d

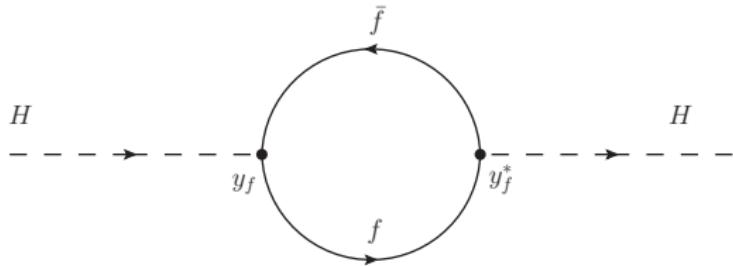
Radiative EWSB



[Martin (1997)]

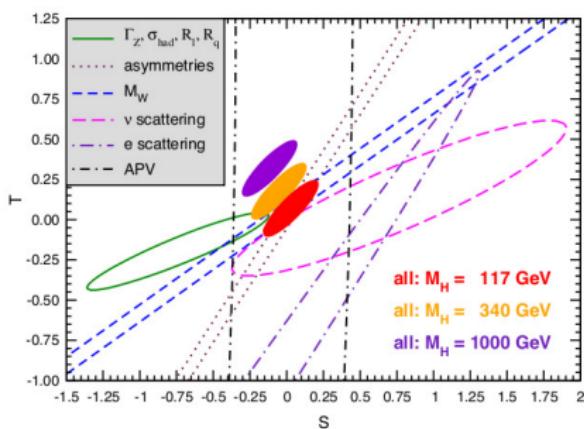
SM Higgs

- ▶ $V = -m^2|H|^2 + \lambda|H|^4$
- ▶ $\frac{\partial V}{\partial H} = 0 \implies \langle |H|^2 \rangle \equiv v^2 = \frac{m^2}{2\lambda}$
- ▶ $m_h^2 = 2m^2$

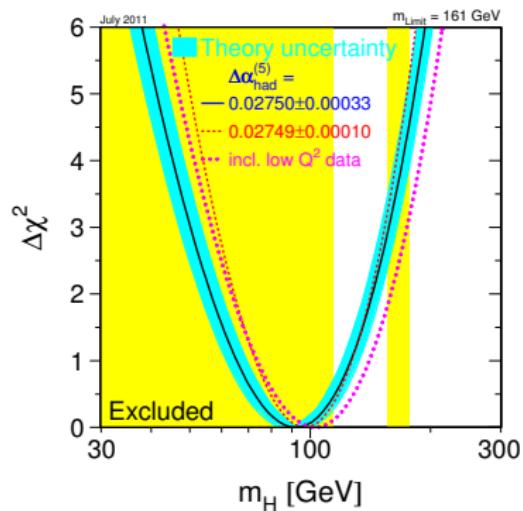


$$\delta m^2 \approx -\frac{N_c}{8\pi^2} |y_f|^2 \Lambda_{UV}^2$$

Precision EW



[Nakamura et al. [PDG] (2010)]



[LEP EW Working Group (2006)]

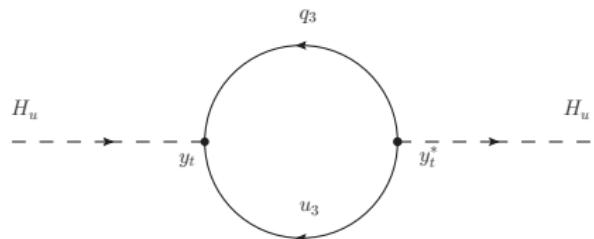
Fine Tuning

$$\begin{aligned} m_0^2 + \delta m^2 &\approx m_h^2/2 \\ \sim M_{\text{GUT}}^2, M_{\text{Pl}}^2 &\sim (100 \text{ GeV})^2 \end{aligned}$$

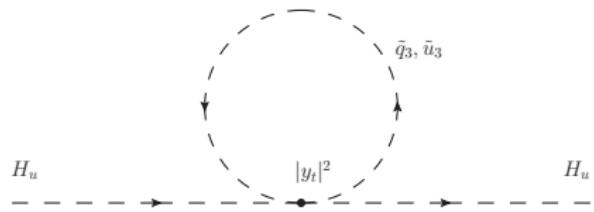
- ▶ 1 part in $10^{28}, 10^{32}$ cancellation
- ▶ “hierarchy problem”
- ▶ How to quantify? How much is too much?

$$\Delta_i \equiv \left| \frac{\partial \ln \hat{O}}{\partial \ln p_i} \right|, \quad \Delta \equiv \max\{\Delta_i\}$$

Fine Tuning in the MSSM



$$\sim -\frac{3}{8\pi^2} |y_t|^2 \Lambda_{\text{UV}}^2$$



$$\sim 2 \times \frac{3}{16\pi^2} |y_t|^2 \Lambda_{\text{UV}}^2$$

- ▶ Diagrams cancel up to SUSY-breaking effects:
$$\delta m_{H_u}^2 \approx -\frac{3}{8\pi^2} (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \ln \left(\frac{\Lambda_{\text{mess}}}{m_{\tilde{t}}} \right)$$
- ▶ Large squark masses re-introduce fine tuning
- ▶ “little hierarchy problem”

Fine Tuning in the MSSM

- ▶ tree level:

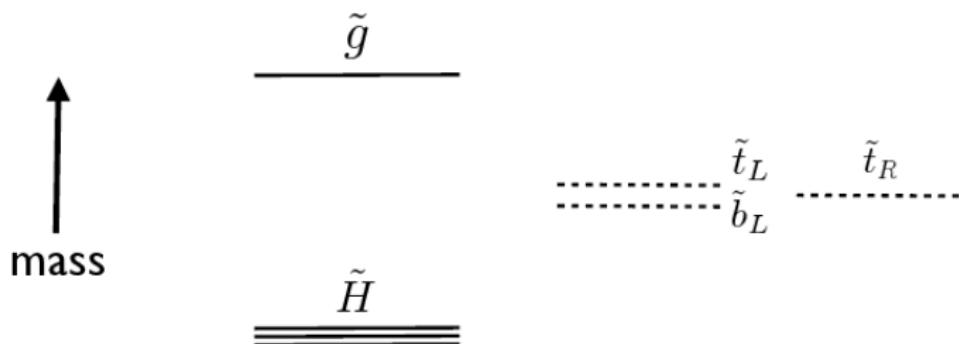
$$\frac{m_Z^2}{2} = - \left(m_{H_u}^2 + |\mu|^2 \right) + \mathcal{O} \left(\frac{1}{\tan \beta^2} \right)$$

- ▶ 1 loop:

$$\delta m_{H_u}^2 \approx -\frac{3}{8\pi^2} \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \ln \left(\frac{\Lambda_{\text{mess}}}{m_{\tilde{t}}} \right)$$

$$\delta m_{\tilde{t}}^2 \approx \frac{8\alpha_3}{3\pi} M_3^2 \ln \left(\frac{\Lambda_{\text{mess}}}{m_{\tilde{t}}} \right)$$

The Natural Spectrum



All other sparticles can be heavy without affecting the naturalness of the theory, ie, 1st and 2nd generation squarks, bino/wino, sleptons

How light?

$$m_{\tilde{t}}^2 \lesssim (400 \text{ GeV})^2 \frac{1}{1+A_t^2/2m_{\tilde{t}}^2} \left(\frac{20\%}{\Delta^{-1}} \right) \left(\frac{3}{\ln(\Lambda/m_{\tilde{t}})} \right) \left(\frac{m_h}{120 \text{ GeV}} \right)^2$$

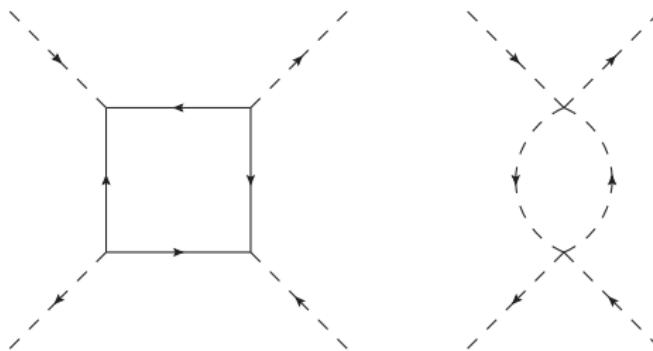
$$|\mu|^2 \lesssim (200 \text{ GeV})^2 \left(\frac{20\%}{\Delta^{-1}} \right) \left(\frac{m_h}{120 \text{ GeV}} \right)$$

$$M_3^2 \lesssim (700 \text{ GeV})^2 \frac{1}{1-A_t/2M_3} \left(\frac{20\%}{\Delta^{-1}} \right) \left(\frac{3}{\ln(\Lambda/m_{\tilde{t}})} \right)^2 \left(\frac{m_h}{120 \text{ GeV}} \right)^2$$

[Kitano and Nomura (2006)]

- ▶ NB: This part depends strongly on taste
- ▶ 8 TeV is a very low messenger scale

Indirect fine tuning measurements: the Higgs mass

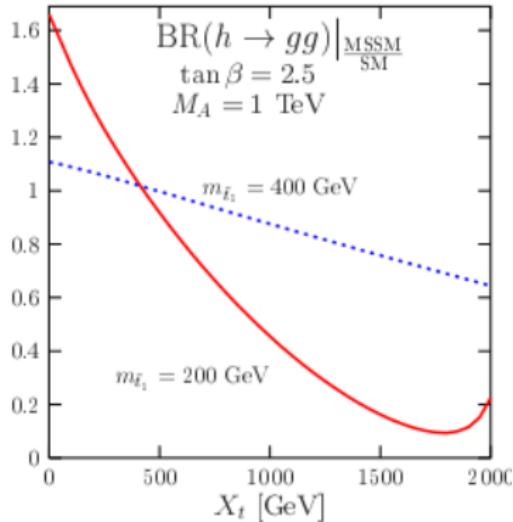


$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[\ln \left(\frac{m_{\tilde{t}}^2}{m_t^2} \right) + \frac{X_t^2}{m_t^2} \left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right]$$

$$X_t \equiv A_t - \mu \cot \beta$$

- ▶ $m_h \gtrsim 114 \text{ GeV} \implies m_{\tilde{t}} \gtrsim 300\text{-}1000 \text{ GeV}$
- ▶ few % fine tuning
- ▶ Physics beyond MSSM can raise higgs mass, too

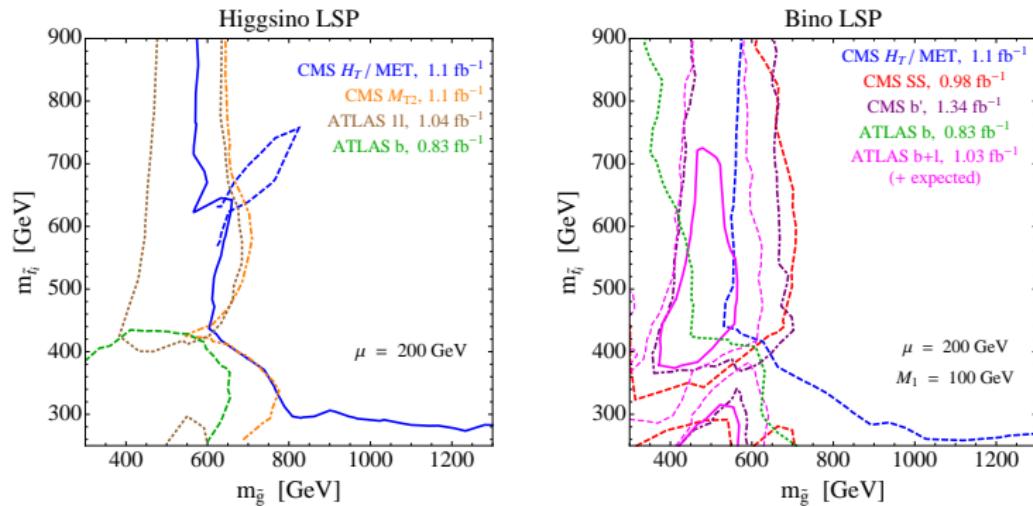
Are we already in trouble?



[Djouadi (2005)]

- ▶ stop mixing can modify the production cross section in either direction
- ▶ other physics, eg non-decoupling, can also modify couplings

Stop limits



[Papucci et al. (2011)]

Conclusions

- ▶ y_t drives EWSB
- ▶ 3rd generation squark masses provide a direct measure of fine tuning in the MSSM
- ▶ Generate important modifications to the higgs mass and couplings
- ▶ Experimental constraints are relatively weak
- ▶ Natural SUSY lives (for now)!